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II

Comments on the ACRS Quantitative Safety Goals

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1.0 Introduction

In October 1980, the Advisory Committee on Reactor Safeguards (ACRS), Subcommittee on Reliability and Risk Assessment, in response to a request from the Nuclear Regulatory Commission, presented a report[1] outlining the concepts of quantitative risk assessment criteria and making recommendations for specific safety goals. Goals are set for the probability of reactor hazard states, risk to an individual, risk to society, and societal impact reduction. In order to incorporate the risk aversion that the public has demonstrated to large potential disasters, a simple risk aversion model is described, and the limit on early deaths is given in terms of early death equivalents which incorporate the risk aversion model.

In this paper the relationship between the ACRS recommendations and widely reported public views is examined. Using the CRAC2[2,3] reactor accident consequence analysis code, frequency distributions for the consequences of a large core melt accident with substantial release were generated. Using these distributions of effects, it appears that the risk aversion level recommended in the ACRS report may not be consistent with public perceptions. In addition, while the ACRS recommendations in the different areas appear reasonable when viewed singly, their interactions lead to conclusions which may not be as widely acceptable as the recommendations. These conclusions are examined and recommendations are made for modifying the approach of the ACRS.

2.0 Recommendations of the ACRS

2.1 Overview

The report of the ACRS[1] is divided into three parts; "On the Development of Quantitative Risk Acceptance Criteria," "Risk Management and Decision Rules for Light Water Reactors," and "Applications and Implications of Trial Risk Acceptance Criteria." The first section of the report gives a general overview of the concepts behind quantification of risk

acceptance criteria. This section discusses the problems of quantifying risk and, perhaps more importantly, the public perception of risk. Alternative approaches to risk criteria are described, and examples are given of applications of risk acceptance criteria in fields other than nuclear power generation.

The second section of the report makes tentative recommendations of specific risk acceptance levels. The basis for determining acceptable risk levels is that the risk from nuclear power generation should be less than background risks as well as those from the alternatives, which are considered to be coal-fired generation only.

The last section of the report analyzes three case studies of applications of risk acceptance criteria. The actual studies are contained in appendices to the report.

2.2 Risk Acceptance Recommendations

The recommended acceptance criteria in section two are divided into four areas; risk of a hazard state, risk to an individual, risk to society, and societal impact reduction. The ACRS states in their report that although the mandate of the NRC is to protect the public health and safety, it is necessary to include acceptance criteria which consider the occurrence of hazard states since they represent the forerunners of potentially serious accidents. These accidents may cause serious economic harm to the utility, and indirectly to the public, and they may cause a traumatic effect on the public. The ACRS report makes a tentative classification of three hazard states of progressively increasing severity. In order of increasing severity, the states are:

> Significant core damage (greater than 10% of noble gas inventory leaking into primary coolant).
>
> Large scale fuel melt (greater than 30% of the oxide fuel becoming molten).
>
> Large scale uncontrolled release of radioactive material (greater than 10% of the iodine inventory plus greater than 90% of the noble gas inventory) from the containment.

For each of these three hazard states a goal and upper limit probability level are proposed. Under the recommendations of the ACRS, plants meeting the goal level would be considered to be in compliance with the proposed guidelines (subject to the ALARA criteria). Plants representing risks above the upper acceptance level would be unacceptable. Those falling in between would be subject to a case by case analysis. The proposed levels for the three hazard states are:

Hazard State	Goal	Limit
Significant Core Damage	3E-4	1E-3
Large Scale Fuel Melt (LSFM)	1E-4	5E-4
Large Scale Uncontrolled Release from Containment given LSFM.	.01	.1

The first two of these criteria are measured in occurrences per reactor year, while the third is measured in occurrences per large scale fuel melt.

The inclusion of criteria on the risk to an individual attempts to provide an equitable distribution of the societal risk. Risk levels are suggested which limit the risk of early death from the existence of the power plant to a level below that caused by background or occupational hazards. The risk to an individual of inducing a cancer death is restricted to 1E-5 per site year. This represents a level of risk almost 100 times lower than the background risk of eventual cancer death. Since the public appears to place a higher cost on an early death (death within a year is perceived as worse than death in 10 to 15 years), a weighting factor of five is placed on early death versus delayed death. The proposed limits on risk to an individual, defined as the most exposed "average" individual are:

Risk	Goal	Limit
Delayed Death from Cancer	5E-6	2.5E-5
Early Death	1E-6	5E-6

(See Reference 1 for further explanation of this table.)

These are probabilities of death per site-year to the most exposed individual. A similar set of figures is given for

deaths per LSFM. These are:

Risk	Goal	Limit
Delayed Death from Cancer	.01	.05
Early Death	.002	.01

The ACRS has deliberately overlapped these goals with the limits on hazard states as well as each other to provide additional protection in the event that some of the analysis of risk is inaccurate.

The third area for which recommendations are made on risk acceptance criteria is societal risk. The public is widely believed to be risk averse when comparing the risks of low consequence, high probability events to those of high consequence, low probability events. The ACRS report recommends use of a model of risk aversion when determining the social cost of early deaths due to a reactor accident. This model assumes that the perceived cost of an event is some power of the consequence; thus

$$\text{Societal Cost} = (\text{consequence})^{a}$$

While studies have been made of the appropriate value of a to represent the public's perception, there is no consistent estimate. The ACRS has chosen $a = 1.2$ for their recommendation. The expected societal risk is therefore:

$$E[\text{Societal Risk}] = \sum_{\text{all accidents}} (\text{frequency}) * (\text{Early Deaths})^{1.2}$$

The expected societal risk for early deaths is measured in early death equivalents. The factor of 5 for the relative values of early deaths versus delayed cancer deaths is also used in societal risk limits. To arrive at a goal level, the societal risk from a site is limited to the lower bound on the estimates for the risk from a comparably sized coal fired generating station. This is estimated as 10 deaths per 10E10 KWh, which is approximately the annual output of a 1200 MWe nuclear power plant. the proposed goals for societal risk are:

Measure of Risk	Goal	Limit
Delayed Cancer Deaths	2	10
Early Death Equivalents	.4	2

The measures of risk are calculated using the risk aversion formula described above, and the units are deaths per 10E10 KWh.

An ALARA (As Low As Reasonably Achievable) condition is provided to insure that improvements in technology will be employed to minimize the risk due to a nuclear power plant. The ACRS recognizes that the damage to resources and property may be significant, but does not feel that the area is sufficiently well understood to suggest a goal and upper limit on economic consequences. Therefore, the ACRS adopts a recommendation for an ALARA condition with respect to economic loss as well as an ALARA condition on health effects to people. A change is required if its cost is less than

$1 million per delayed cancer death averted

plus

$5 million per early death equivalent averted

plus

2 times the economic loss averted.

The first and third terms are measured in expected value while an early death equivalent incorporates the 1.2 risk aversion factor used in defining societal risk.

3.0 Risk Calculations

Using the CRAC2 (Calculation of Reactor Accident Consequences) code, we have examined the impact of the proposed quantitative safety goals on the siting of nuclear power reactors. CRAC2 is an update of CRAC, the code developed for the Reactor Safety Study[4]. A number of the submodels have been improved and the data describing the health effects has been modified to take into account current views. The costs used in the economic model have been updated, as best as possible,

to reflect 1980 values. Details about the CRAC2 code and its differences from CRAC can be found in the Siting Study Report[2] and the CRAC2 User's Guide.[3] For a hypothetical 1100 MWe PWR, an LSFM with uncontrolled release was assumed with the source term described below.

Time of Release (hr)	Release Duration (hr)	Warning Time (hr)	Release Height (meters)	Release Energy
1.5	2	0.5	10	0

Core Inventory Release Fractions (to atmosphere)

Xe-Kr	I	Cs-Rb	Te-Sb	Ba-Sr	Ru	La
1.0	.45	.67	.64	.07	.05	9E-3

(These headings refer to RSS[4] inventory groups)

(There is considerable controversy about the nature of the source term for this type of release. There is some belief that the chemistry of the release process, independent of any safety features, will act to reduce these release fractions significantly.[5])

Using this source term, consequences were calculated using the characteristics of the Indian Point site (population distribution surrounding the reactor, local meteorology, and site wind rose). The population around the site was assumed to be evacuated to a distance of 10 miles at a speed of 10 miles per hour, with a delay of 1, 3, or 5 hours. These three scenarios were combined with a 30%, 40%, 30% weighting for the results presented here. Contaminated land was assumed to be interdicted if the lifetime dose to a resident would exceed 25 rem. Further details about these runs can be found in Reference 2. Similar calculations were performed for the Zion and Limerick sites, using the characteristics specific to those sites. In each case, the 1100 MWe reactor and source term were used rather than the reactors that actually exist at the site, which may in fact be either more or less safe than the hypothesized reactor. The consequences of the accident are summarized below. The number of early deaths is stated both in terms of mean number given the accident, and early death equivalents given the accident, which is calculated by summing over the distribution of accidents, the consequence raised to the 1.2 power times the probability of the accident,

thus incorporating the risk aversion formula recommended in the ACRS report.

Site	Mean Early Deaths	Early Death Equivalents
Indian Point	750	4000
Limerick	900	5000
Zion	490	2100

4.0 Implications of the ACRS Risk Criteria

Limerick, which has the largest number of early death equivalents, has an expected rate of .005 early death equivalents per reactor-year for a reactor meeting the hazard state goals of the ACRS report. This is two orders of magnitude below the recommendations of the ACRS. In order to determine the limits on population density for a site which satisfies the proposed ACRS goals, we analyzed a site with a .5 mile exclusion radius surrounded by a population of uniform density. An 1100 MWe PWR meeting the ACRS goals for hazard state was assumed to exist at the site, and the source term for the accident is the same one used in the Indian Point, Limerick, and Zion studies. This hypothetical site satisfied the ACRS goal criterion on early death equivalents for population densities up to 38,000 people per square mile, and met the goal criterion for delayed deaths for population densities up to 143,000 people per square mile.* These figures imply that in even the most densely populated metropolitan areas the ACRS criteria would be satisfied. This is apparently at variance with established national policy on the siting of nuclear power reactors.

There are a number of possible explanations which, alone or in combination, may account for the high population densities allowable under the ACRS recommendations. The hazard state probabilities could be unrealistically optimistic, the risk goals not sufficiently conservative, the recommended risk aversion formula may not accurately model public perception of risk, or CRAC2 predictions could be grossly inaccurate. (CRAC2 uses a straightline Gaussian plume model for dispersion which, except in complex terrain, is believed to be accurate within an order of magnitude.)

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*These figures are based on the simplifying assumption that evacuation effectiveness is independent of population density. A more sophisticated model may arrive at lower figures.

Comments on the ACRS Quantitative Safety Goals

4.1 Hazard State Probabilities

The ACRS goal for probability of a large scale fuel melt with uncontrolled release from containment is 1E-6. As a comparison, the Reactor Safety Study accident categories which roughly correspond to the definition of the LSFM with uncontrolled release have a summed probability approximately 14 times the ACRS level. Even using the RSS hazard state probabilities in place of the ACRS goal would lead to allowable population densities in excess of current national siting policy.

4.2 Risk Goals

The setting of a societal risk goal is inherently a socio-political task rather than a technological one. The ACRS has chosen the upper acceptance limit on the expected number of delayed deaths from a nuclear power plant to be equal to the low end of the estimated range of deaths due to air pollution from a coal fired plant of comparable capacity. The limit on early death equivalents is set 5 times lower. It is believed that the number of potential early deaths in a single incident plays a significant role in public perception of the magnitude of a risk. An attempt to account for this factor is made by including a risk aversion formula, and limiting "equivalent" deaths. Selection of a risk aversion formula, however, may be subject to controversy since it will play a significant role in determining which risks are acceptable and which are not.

The ACRS has proposed a formula which raises the consequences to an exponent. The recommended value for the exponent is 1.2. As the ACRS recognized, the sensitivity to this exponent is considerable, and the acceptability of a site can change radically by changing the exponent a comparatively small amount. The graph below (similar to Figure A.7 in [1]) plots the number of early death equivalents at Indian Point given the occurrence of an LSFM with uncontrolled release for a number of different exponents. Changing the exponent from 1.2 to 1.7 changes the number of equivalent deaths from about 4,000 to almost 400,000, a change of two orders of magnitude. This is the amount of change necessary to make Indian Point marginal with respect to the ACRS upper acceptance limit on early death equivalents if a reactor satisfying the hazard state goal were to be located there. Similarly, Limerick requires an exponent of 1.65 and Zion an exponent of 1.85 in order to be considered marginal under the proposed guides. One might argue that empirically these values are more appropriate than 1.2 as exponents for a risk aversion function of the form recommended in the ACRS report.

Comments on the ACRS Quantitative Safety Goals

Some may wish to consider an alternative to the form of the ACRS, rather than just a change in exponent. However, until such alternatives are provided we cannot perform a similar analysis of their impacts and sensitivity.

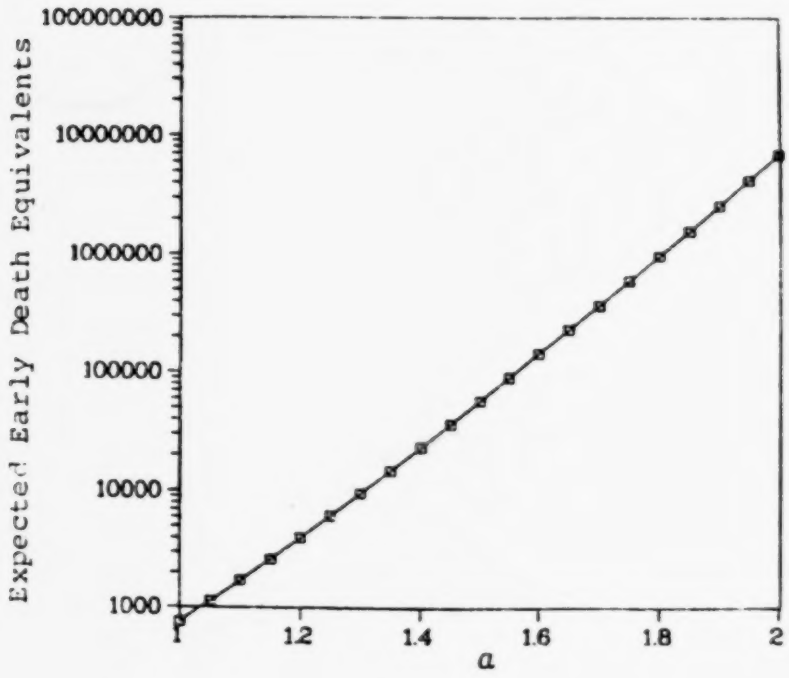

Figure 1.

4.3 ALARA Criteria

The ALARA criteria are included to insure that cost effective improvements are implemented, even after the safety goals have been met. Recent court awards in suits seeking compensation for deaths stemming from malpractice, accidents, or criminal activities would seem to indicate that a $5 million valuation on a prevented early death would probably be conservative. The $1 million for delayed death is harder to compare, since there are few precedents for awards to individuals for life shortening, at least until the death has actually occurred. However, in comparison to the typical award of compensation for an early death, the $1 million

level would cover the majority of the cases, and therefore appears to be reasonable. The economic loss term requires an improvement be made if its cost is less than twice the expected loss averted. This one-for-two expected payoff requires a strong degree of risk aversion to be considered a fair bet.

The ACRS goal for early death equivalents is .4 per 10E10 KWh, which is approximately the annual output of a 1200 MWe plant operating 100% of the time. Assuming a 30 year reactor life, this allows about 12 early death equivalents per reactor lifetime. Not including any discounting factor, this allows a budget of $60 million for modifications to reduce risk to zero. If we factor in availability, which typically is 70-80%, this figure will be reduced. If present-value discounting is permitted, the liability under the ALARA criterion will be further reduced. Factoring in a 15% annual discount rate, the limits on expenditure to reduce the .4 early death equivalents per year to zero for the plant life is only $13 million. Since it is impossible to reduce the early death figure to zero (this would imply a risk-free plant), liability will be under the $13 million figure. A similar analysis for the delayed death criterion leads to identical figures due to the ACRS's use of the multiplier of 5 between early death goals and value and the corresponding goals and values for delayed deaths.

These figures are based on a reactor exactly meeting the ACRS goal for early death equivalents (or delayed cancer deaths). The risk calculations presented earlier indicate that sites may actually be two orders of magnitude below these goals. In that case the liability would be reduced by two orders of magnitude, to approximately $0.6 million for early deaths and $0.6 million for delayed cancer deaths (for the undiscounted case).

The ALARA condition for averting economic loss must be compared to the limits on the occurrences of hazard states. The occurrence of a large scale fuel melt is limited to 1E-6 per reactor year, or roughly 3E-5 per reactor life. The CRAC2 analyses described earlier calculate an expected economic loss of approximately $8E10 for a major accident similar to the LSFM with uncontrolled release. (Note that the CRAC2 economic model is crude and subject to large uncertainties.) Therefore, the undiscounted present value of reducing the economic loss to zero is about $2.4 million. The discounted present value of this figure, using a 15% discount rate, is only a little over $.5 million. (It is important to note here that CRAC2 does not account for replacement power or reactor cleanup costs in the economic model. Because of the probability of occurrence, a small accident (e.g., TMI) may actually dominate expected losses.)

The limited liabilities under the ALARA criteria would be likely to force attention on minor design modifications or procedural improvements which reduce the probability of an accident rather than on expensive hardware fixes which seek to mitigate the consequences in the event of the occurrence of an accident.

5.0 Summary

While the analysis behind each of the criteria in the ACRS report seems reasonable, the recommendations, when viewed with respect to additional data regarding accident consequences and the interactions of the criteria, lead to some conclusions which were not obvious. When the hazard state goals are combined with estimates of consequences of accidents, the risks appear so minimal that the risk criteria proposed in the ACRS report allow siting in apparent conflict with existing and proposed siting policy. Thus while the ACRS recommendations seem to provide a useful framework for a more acceptable licensing procedure, some of the details may have to be changed to resolve conflicts with national siting policies.

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